The discoveries of W and Z

Carlo Rubbia

CERN,Geneva, Switzerland

W and Z with ppbar collisions: an historical review

1. From intersecting storage rings to colliders

2. Non Liouvillian vs. Liouvillian compression: stochastic cooling

3. P-pbar collisions:will they permit a reasonable beam-beam tune shift and hence an acceptable luminosity ?

4. The difference of beam-beam interactions: e^+-e^- vs. p-pbar

5. The problem of detecting the signatures for W and Z

6. The impact of p-pbar colliders in modern high energy physics

From storage rings to colliders

- The idea of colliding beams to improve centre of mass energy is due to Wideroe (1943)
  - German patent !
- Main conceptual progress in the fifities
  - MURA
  - Frascati (Touscheck)
  - Novosibirsk (Budker)
- **Two great skepticisms**:
  - Luminosity (rates) and
  - Beam-gas background

Event rate

- Colliding beams event rate R(events/sec) for a cross section σ is given by the formula:

Beam radius

$$R = (n_1 n_2 f_o)(\sigma / A) \quad A = \text{"}beam \;\; area\text{"} = \pi\rho^2/4$$

Number of stored particles

Revolution freq.

$$\sigma = particle \text{ "}area\text{"}$$

- "Brute force" method: accidental encounter of 2 particles of cross section area ($\sigma \approx 10^{-34}$ cm^2) within beam size of $\rho \approx 0.01$ cm.
  - "Geometrical" factor:
  - Very large $n_1 n_2$ product to overcome "geometry effect"

$$(\sigma / A) \approx 10^{-31}$$

Beam-beam vs. beam-gas

- The "density" of the colliding bunch must be much larger than the one of the residual gas: for a bunch of length $L \approx 1$m, of volume V and $n_1 \approx 10^{11}$ particles:

$$d = n_1 / V = n_1 \Big/ \left[\left(\pi \rho^2 / 4 \right) L \right] \approx 3.18 \times 10^{12} \, p / cm^3$$

corresponding to a H gas of pressure of 10^{-4} Torr

- A very large technological advance in the "then" vacuum technology was mandatory

Liouville's constraints

- Already at MURA it was quickly realised that some beam phase-space compression was required from the source to the collisions (O'Neill, Piccioni, Symon).
- *Liouville theorem*: whenever there is an *Hamiltonian* (i.e. for forces derivable from a potential) then:

$$\dot{q}_i = \frac{\partial H}{\partial p_i} \; ; \; \dot{p}_i = -\frac{\partial H}{\partial q_i}$$

Hamiltonian formalism

$$\frac{dV}{dt} = \int \prod_i dq_i dp_i \sum_i \left(\frac{\partial \dot{p}_i}{\partial p_i} - \frac{\partial \dot{q}_i}{\partial q_i} \right) = \int \prod_i dq_i dp_i \sum_i \left(\frac{\partial^2 H}{\partial p_i \partial q_i} - \frac{\partial^2 H}{\partial q_i \partial p_i} \right) = 0$$

The rate of change of Volume is equal to the volume integral of its divergence

⇨ *Both magnetic and electric fields in accelerators (conservative forces) are generally derivable from an Hamiltonian: constant phase-space (at best) !*

- Assume a non -Liouvillian drag force working against the particle speed:

$$\dot{q}_i = \frac{\partial H}{\partial p_i} \;;\; \dot{p}_i = -\frac{\partial H}{\partial q_i} + F_i \;; \qquad \vec{F} = -F(r,t)\frac{\vec{p}}{|p|}$$

← Dissipative, drag force

$$\frac{dV}{dt} = \int \prod_i dq_i dp_i \sum_i \left(\frac{\partial \dot{p}_i}{\partial p_i} - \frac{\partial \dot{q}_i}{\partial q_i} \right) = \int \prod_i dq_i dp_i \sum_i \frac{\partial F_i}{\partial p_i} = -2\frac{F(r,t)}{|p|}$$

Since $dp = \overline{F}\,dt$, integrating we get $dV/V = (2/p)dp$ or

Reduction in phase space

$$V_f / V_i = \left(p_f / p_i \right)^2$$

← reduction in momentum

i.e. phase-space and momentum are *both* reduced.

We can compress phase-space if an accelerating cavity is continuously compensating for the momentum losses due to the drag force

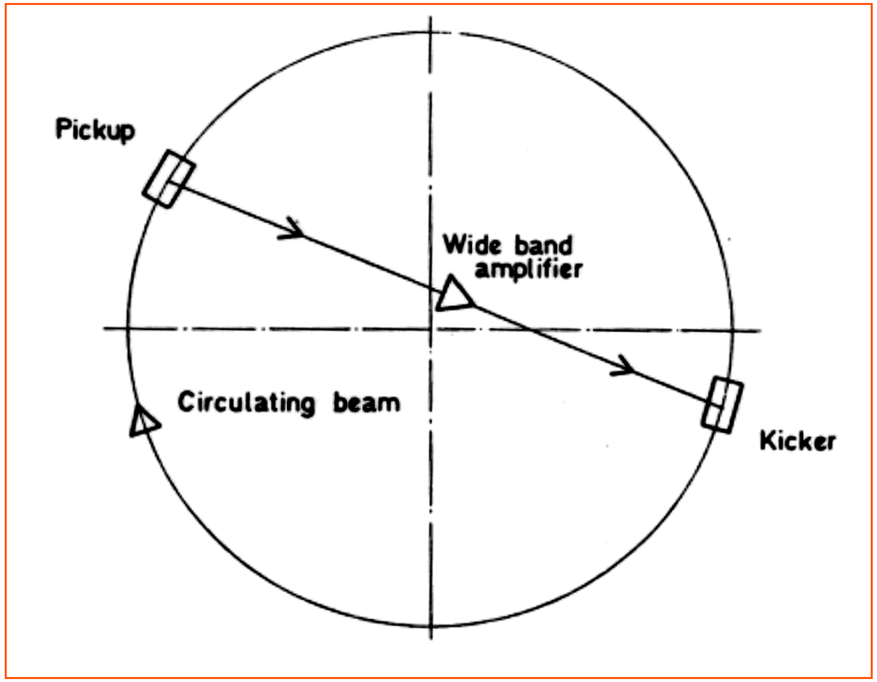
- A physical foil, initially proposed by Piccioni, is inadequate since it introduces multiple scattering and nuclear absorption due to the presence of nuclei. Therefore two possibilities of non Liouvillian cooling are well known:
  - ⇨ Drag force due to *Synchrotron radiation*, which is very powerful for electrons and positrons but absent for p-pbar
  - ⇨ Drag force due to *Electron cooling*, in which a collinear electron beam bath travelling with the particle speed is in contact with the circulating beam (Budker)
- In our case however the winning method has been an entirely new, purely Liouvillian *cooling*, which makes a clever use of the random fluctuations in a finite number of particles.

Stochastic cooling (Van Der Meer)

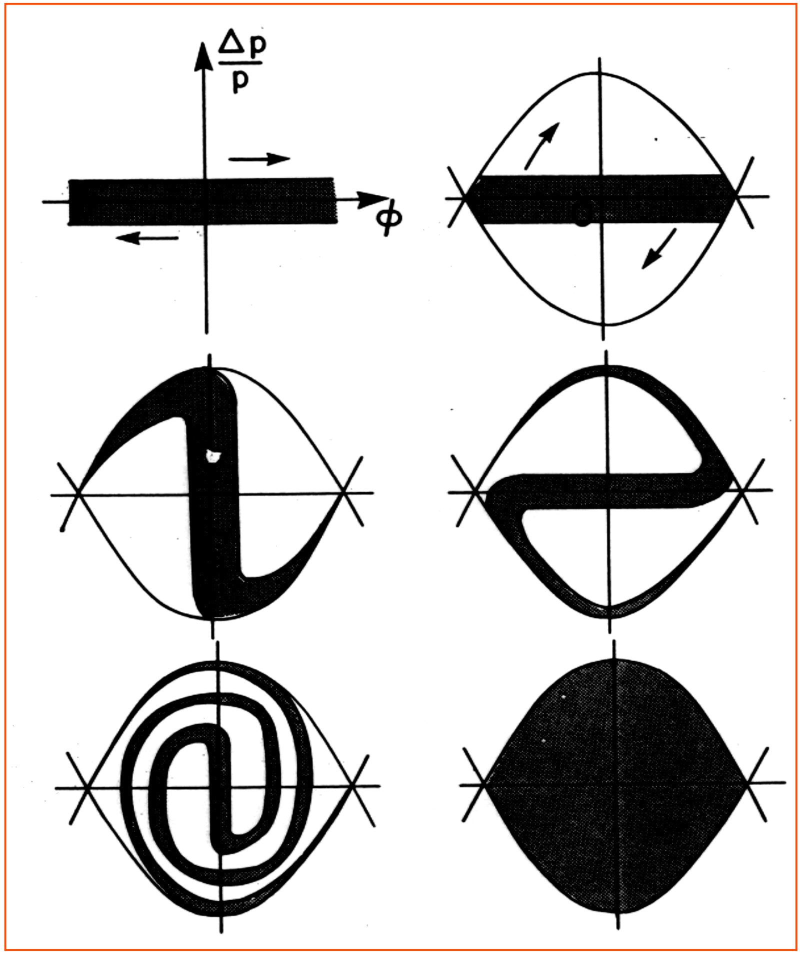
- The stochastic cooling is taking full advantage of the fluctuations inherent in a finite number of particles, which cause a continuous fluctuation in the average position of the local particle sample.

⇨ At each passage, the "kicker" corrects the average value measured by the "pick-up" to zero.

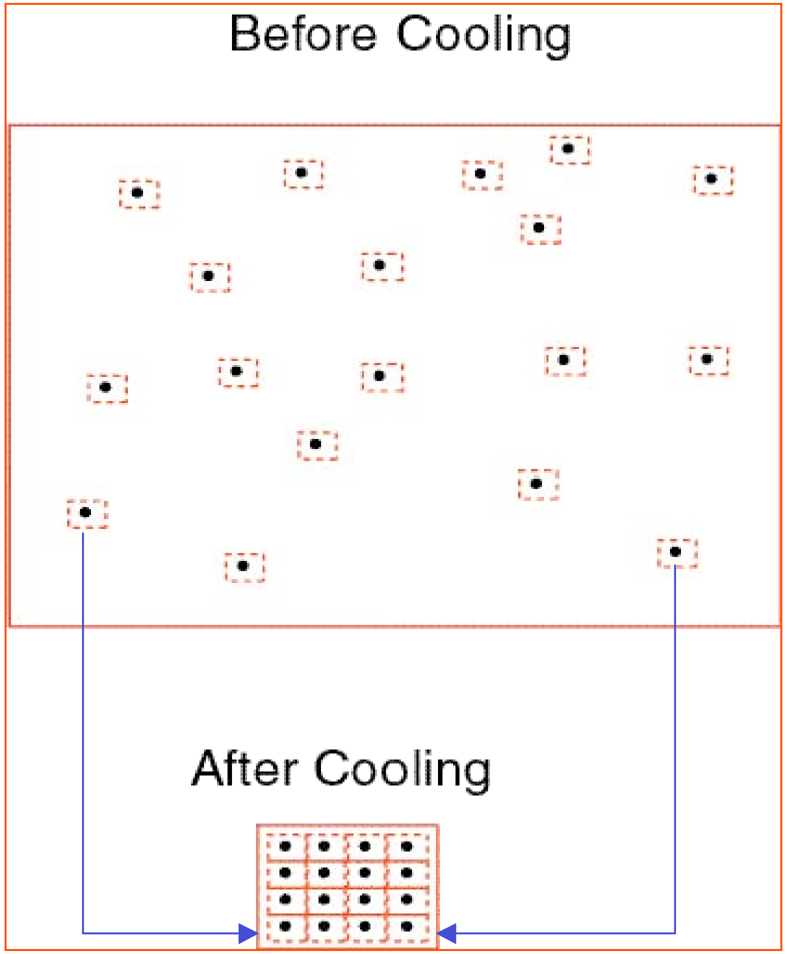
⇨ Needs a continuous "randomizer" of the sample, naturally provided by the momentum spread (mixing) i.e. *memory must be short* !



Filamentation

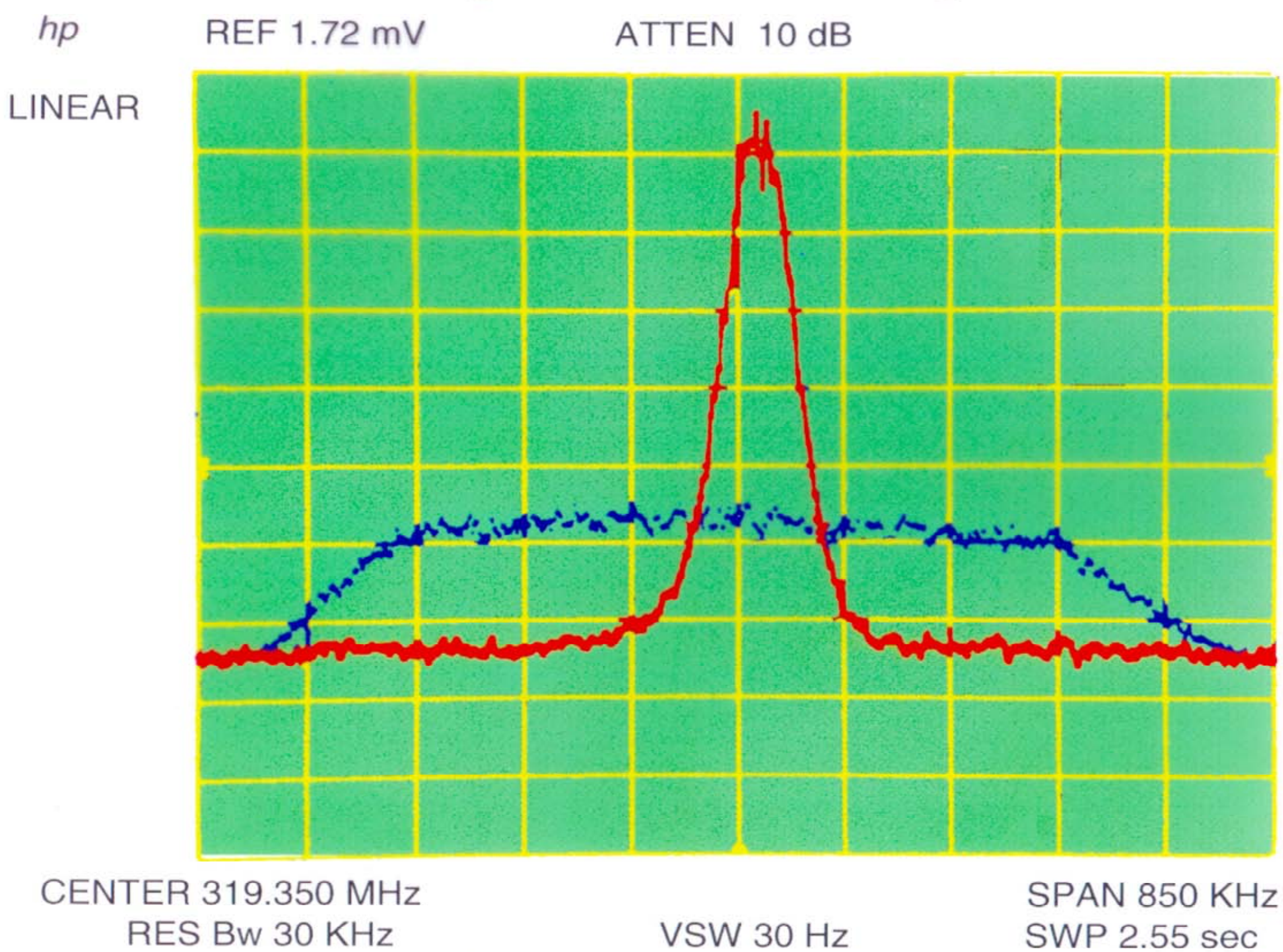


Stochastic cooling



Those tiny pieces of phase-space which contain a particle are pushed closely together. Liouville's theorem is fulfilled !

Antiproton cooling in 2 sec !



Precooling 6 x 10^6 $\bar{p}$'s in 2 seconds. Longitudinal Schottky band at the 170th harmonic (314 MHz) before and after cooling.

Can a collider survive without continuous cooling ?

- In a e^+-e^- collider, cooling is permanently active during collisions: this is not the case for p-pbar: serious concern was voiced regarding the instability of the beams due to beam-beam interactions.
- The beam-beam force can be approximated as a periodic succession of extremely non linear kicks.
- Consider the action invariant (emittance)of a weak p-bar beam crossing an intense proton bunch:

$$W = \gamma x^2 + 2\alpha x x' + \beta x'^2$$

- The effect of the kick $\Delta x'$ on the emittance is

$$\Delta W = \beta\left(\Delta x'\right) + 2\left(\alpha x + \beta x'\right)\Delta x'$$

- This can be expressed in terms of tune shift ΔQ

$$\Delta Q = \Delta x' \beta / 4\pi x$$

- If we assume that successive kicks are randomised

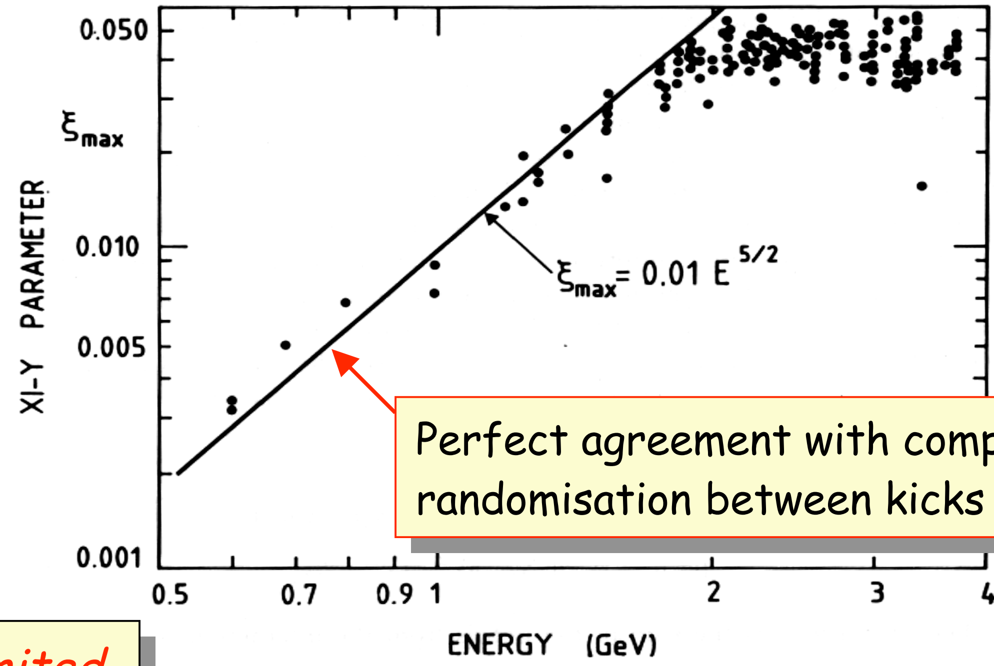
$$\langle \Delta W / W \rangle = 1/2 (4\pi \Delta Q)^2$$

- For ΔQ ≈ 0.003, we get ΔW/W =7.1 10^{-4}, corresponding to a 1/e growth after 1.41 x 10^3 kicks (≈ 45 ms !!)

The SPEAR experiment:

with longer synchrotron damping time due to decreasing energy, the maximum allowed tune shift and hence the luminosity is dropping dramatically.

Extrapolation at p-pbar would imply $\Delta Q < 10^{-6}$



Perfect agreement with complete randomisation between kicks !

P-pbar collisions will only have a very limited use because of their negligible luminosity

The p-pbar collider operates with $\Delta Q \approx 8 \times 10^{-3}$: Why ?

- What is the reason for such a striking contradiction between behaviours with p-pbar and extrapolated prediction from e^+-e^- , which would necessarily imply $\Delta Q \leq 10^{-6}$, thus reducing the maximum acceptable luminosity by a factor as large as 1:8000 ?

  ⇨ for e^+-e^-, emission of synchrotron photons is a major source of quick randomisation between crossings leading to rapid deterioration of beam emittance, but providing also cooling.

  ⇨ For p-pbar, *both* the randomising and the damping mechanisms are absent: the beam has a very long "memory" and kicks are added coherently (periodically) rather than at random

Hadron collisions: how "dirty" ?

- The pessimism about operability of the p-pbar collider without continuous cooling was conjugated with a *widespread lack of confidence in hadron collisions* (ISR), when compared for instance with e^+ -e^-.
  - Dick Feynman used to say that colliding hadrons would be like colliding two "swiss watches"
  - A famous SLAC physicist wrote me a letter saying that with p-pbar we shall never find neither the W, because the background was to large, nor the Z, because the cross section was too small (SPEAR e^+-e^- evidence)
  - Another famous physicist, then the head of the CERN Theory Division, named publicly our project

C(ern) **R**(ings) **A**(ntiproton) **P**(roton)

UA1-The first of a new breed of detectors for hadron colliders

- The reason of lack of success of ISR –where most of the discoveries were missed – was due to insufficient quality of detectors
- Detection for e^+-e^- was simple, since the events are already selected in the s-channel
- In the hadronic channel one is in presence of a high background, since σ_{inel} = 3 x10^{-26} cm^2 and $\sigma_{W,Z}$ = 10^{-34} cm^2 ➡ signal/noise = 3 x10^{-9}.

➥ *Trigger problem*

➥ *Signature problem*

52 authors !

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/SPSC/78-06
SPSC/P92
30 January 1978

PROPOSAL

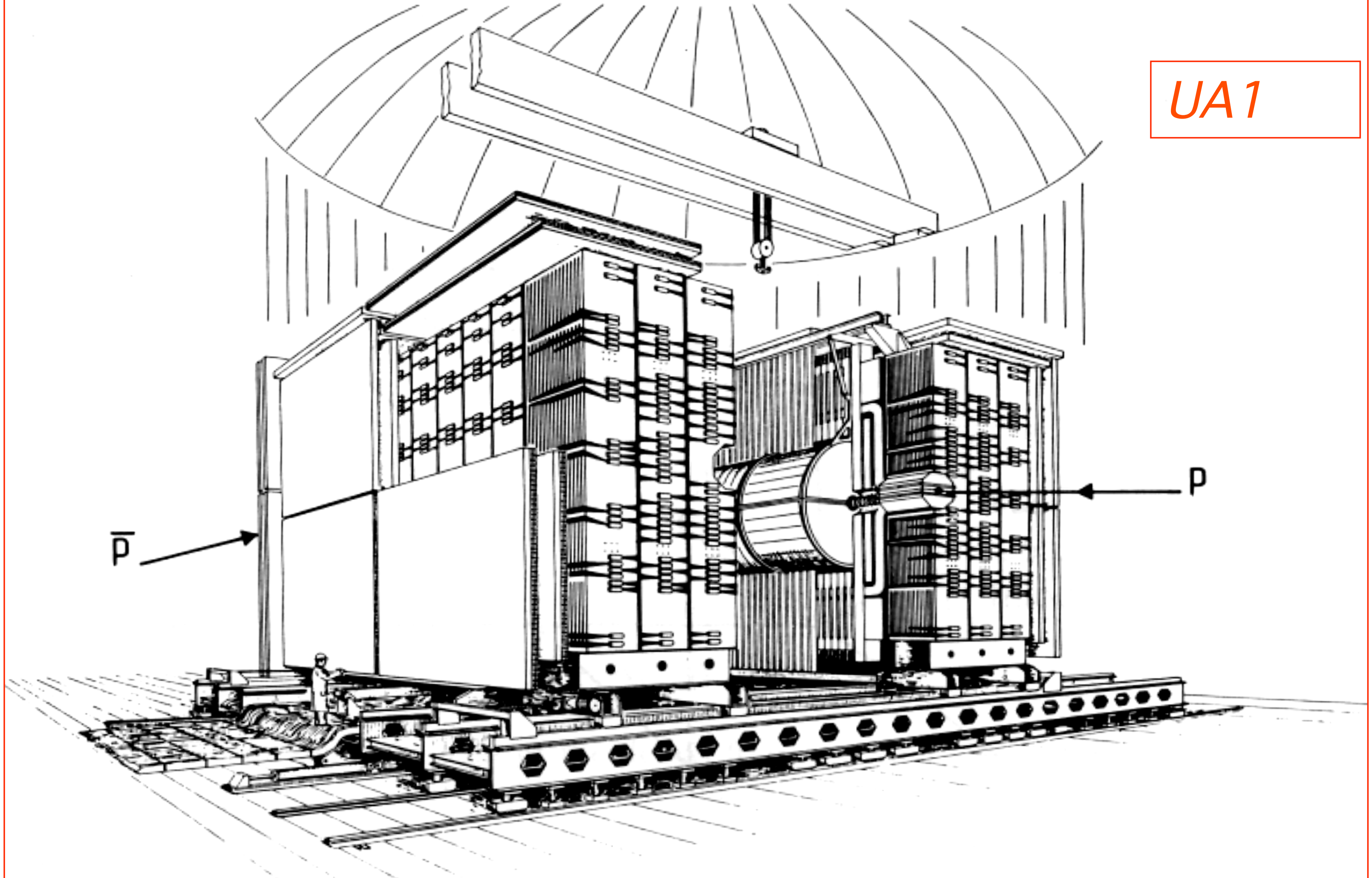
A 4π SOLID ANGLE DETECTOR FOR THE SPS USED AS A PROTON-ANTIPROTON COLLIDER AT A CENTRE OF MASS ENERGY OF 540 GeV

A. Astbury[8], B. Aubert[2], A. Benvenuti[4], D. Bugg[6], A. Bussière[2], Ph. Catz[2],
S. Cittolin[4], D. Cline[*)4], M. Corden[3], J. Colás[2], M. Della Negra[2],
L. Dobrzynski[5], J. Dowell[3], K. Eggert[1], E. Eisenhandler[6], B. Equer[5],
H. Faissner[1], G. Fontaine[5], S.Y. Fung[7], J. Garvey[3], C. Ghesquière[9],
W.R. Gibson[6], A. Grant[4], T. Hansl[1], H. Hoffmann[4], R.J. Homer[3], M. Jobes[3],
P. Kalmus[6], I. Kenyon[3], A. Kernan[7], F. Lacava[**)4], J.Ph. Laugier[9],
A. Leveque[9], D. Linglin[2], J. Mallet[9], T. McMahon[3], F. Muller[4], A. Norton[4],
R.T. Poe[7], E. Radermacher[1], H. Reithler[1], A. Robertson[8], C. Rubbia[†)4],
B. Sadoulet[4], G. Salvini[**)4], T. Shah[8], C. Sutton[8], M. Spiro[9],
K. Sumorok[3], P. Watkins[3], J. Wilson[3], R. Wilson[***)4]

III Physikalisches Institut, Technische Hochschule Aachen, Germany.[1]
LAPP (IN2-P3), Annecy, France.[2]
University of Birmingham, U.K.[3]
CERN, Geneva, Switzerland.[4]
Laboratoire de Physique Corpusculaire, College de France, Paris.[5]
Queen Mary College, London, U.K.[6]
University of California, Riverside, California, USA.[7]
Rutherford Laboratory, Chilton, Didcot, Oxon, U.K.[8]
Centre d'Etudes Nucléaires, Saclay, France.[9]

(Aachen-Annecy-Birmingham-CERN-College de France-Queen Mary College-Riverside-Rutherford-Saclay Collaboration)

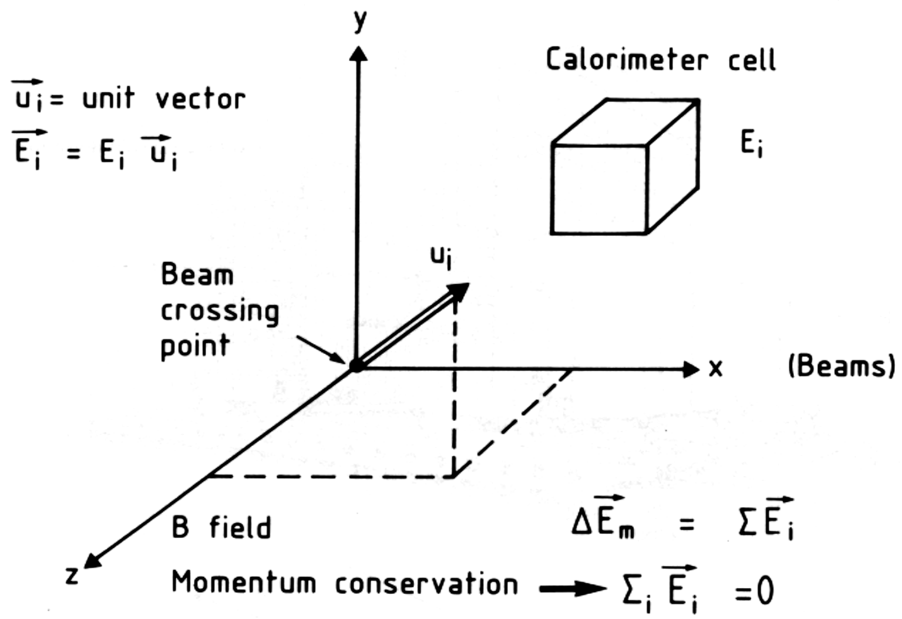
*) Visitor from University of Wisconsin, Madison, Wisconsin, USA.
**) Visitor from University of Roma, INFN Roma, Italy.
***) Visitor from Harvard University, Cambridge, Mass., USA.
†) Spokesman.

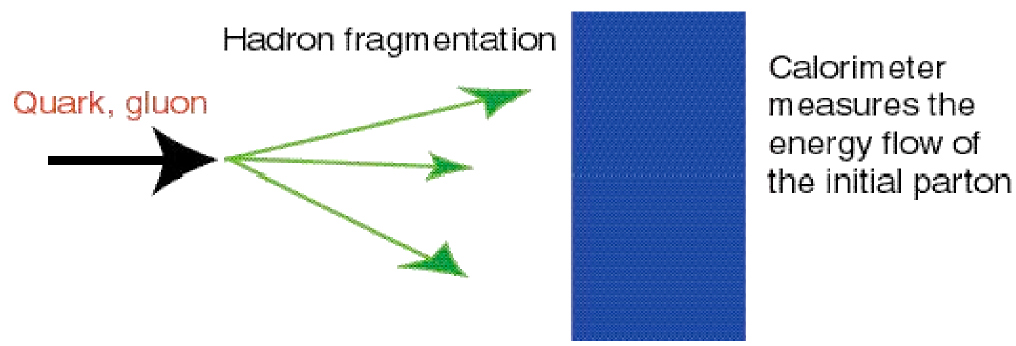


UA1

Major innovations

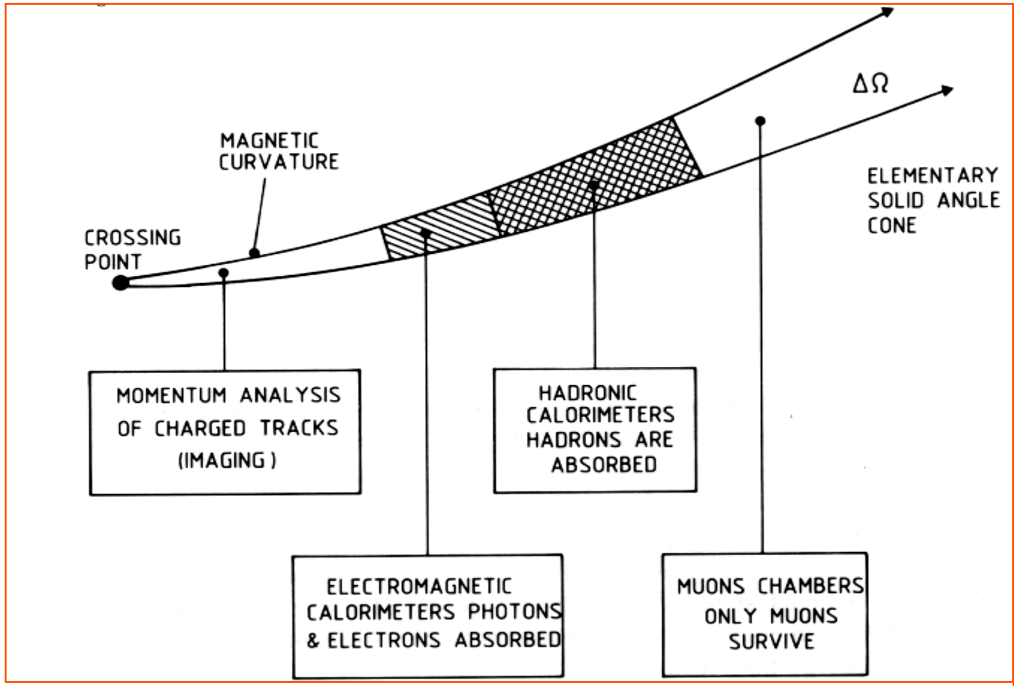
- Look directly at constituents (quarks and gluons) beyond fragmentation, with the help of a sophisticated 4 π calorimetry ➡ *Energy flow*

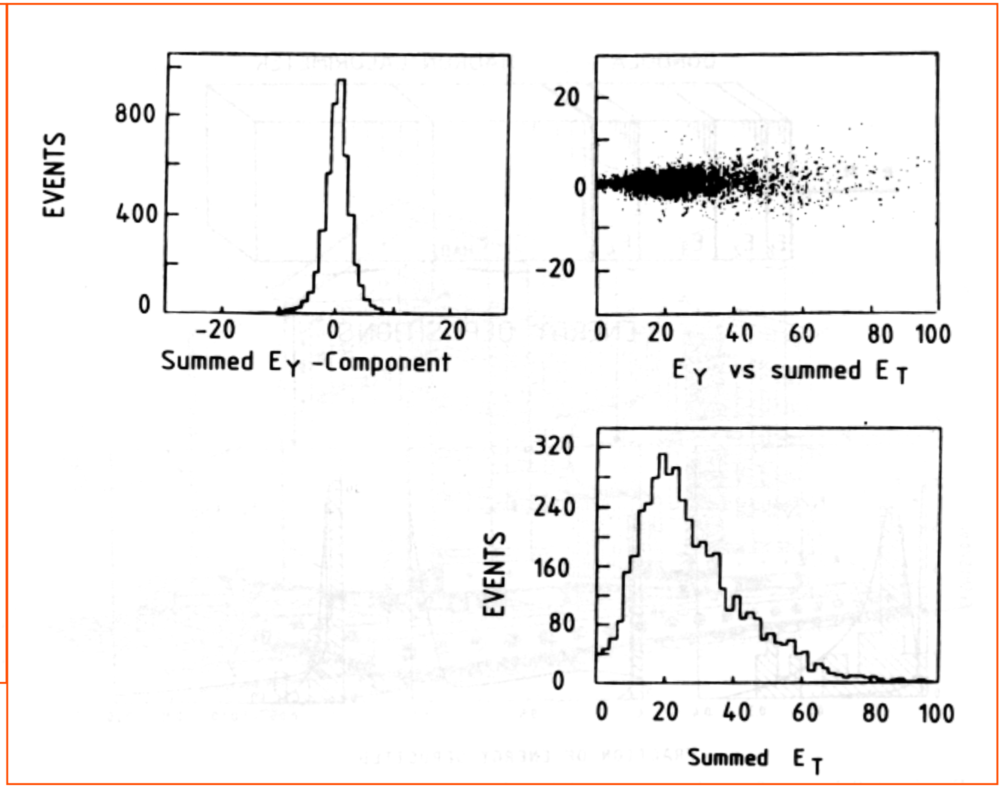




- Missing energy to identify escaping neutrino or non interacting particles ➡ *"Ermeticity" down to 0.2 °*

Hadronic events

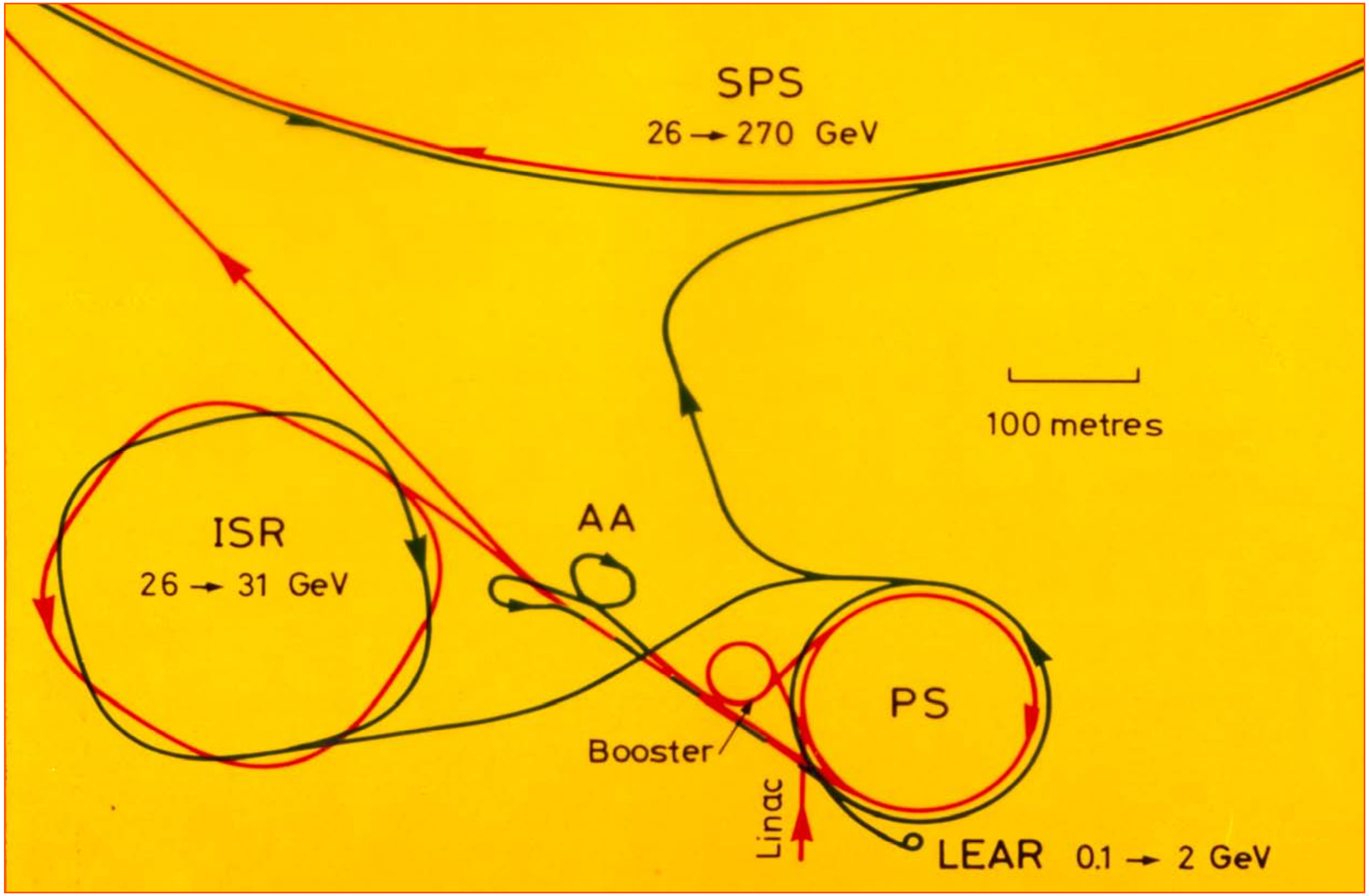




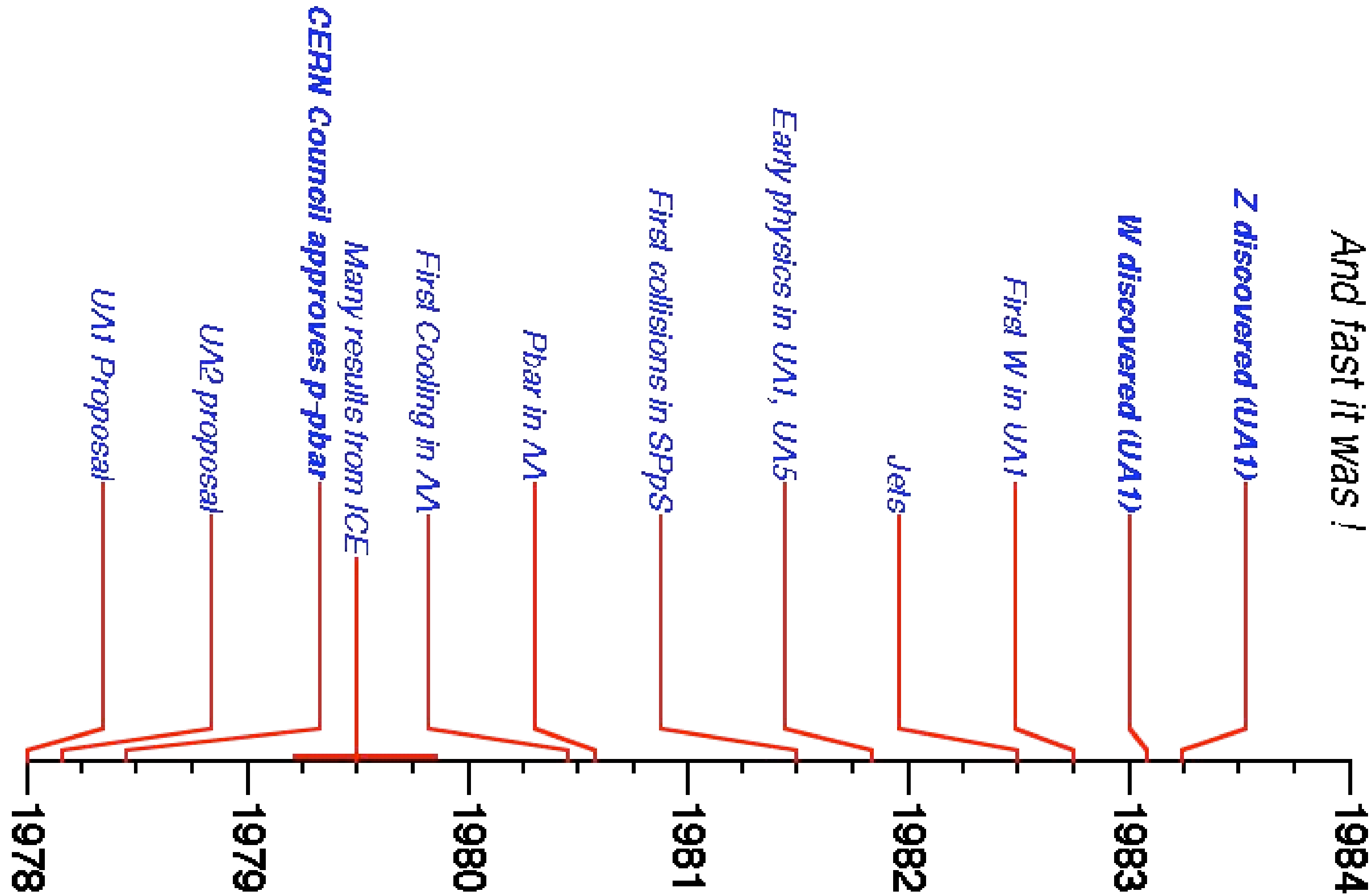
Schematic function in each of the elementary solid angle elements constituting the detector's structure

Over all energy balance for ordinary events

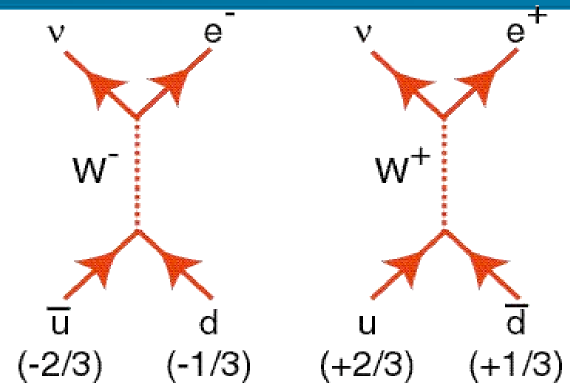
CERN p-pbar Complex

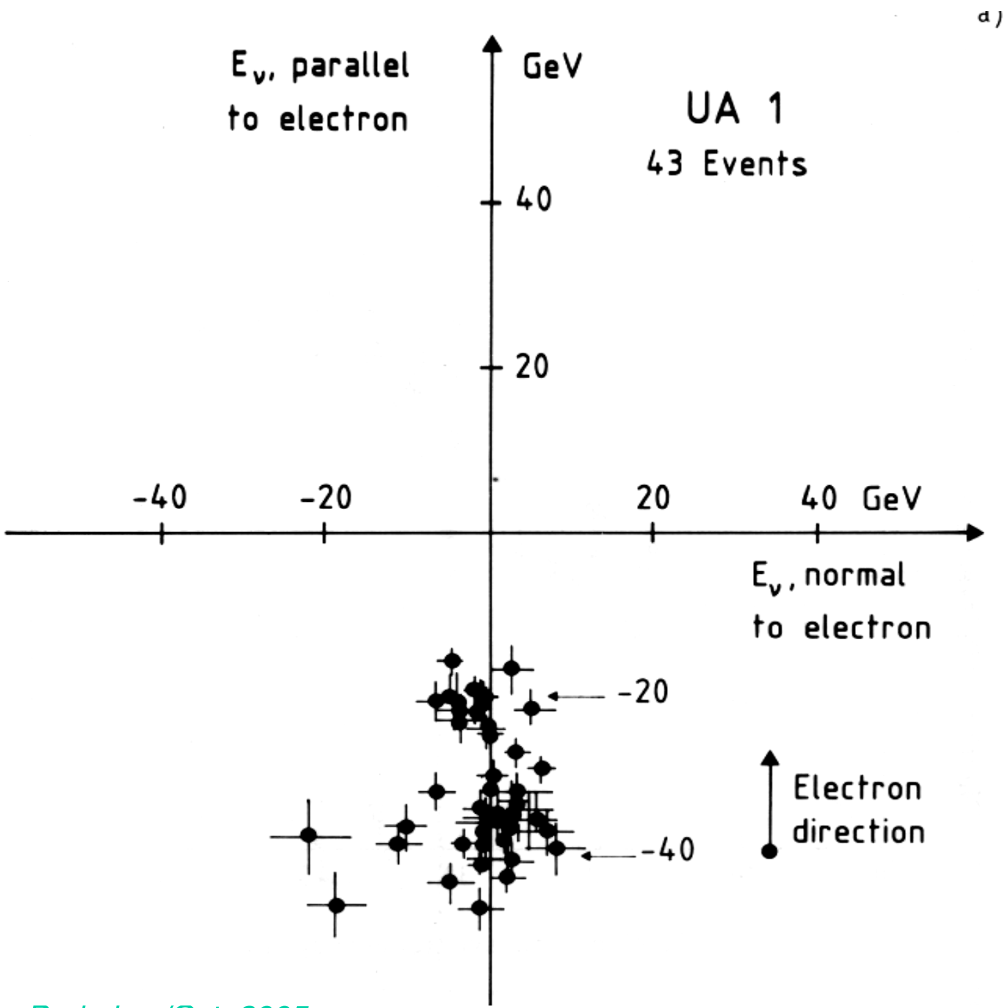


And fast it was !

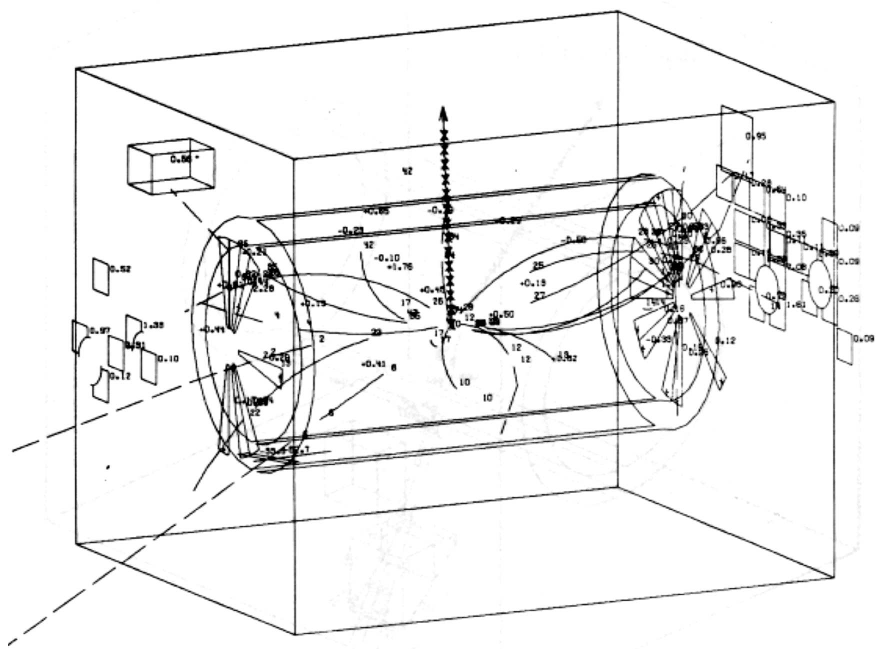


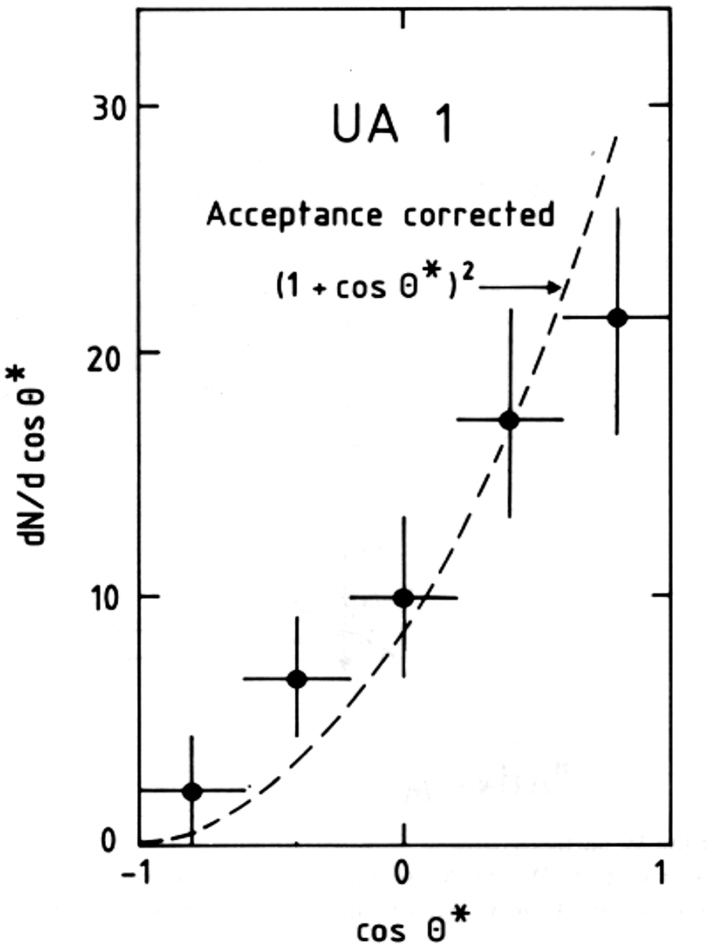
The W signal

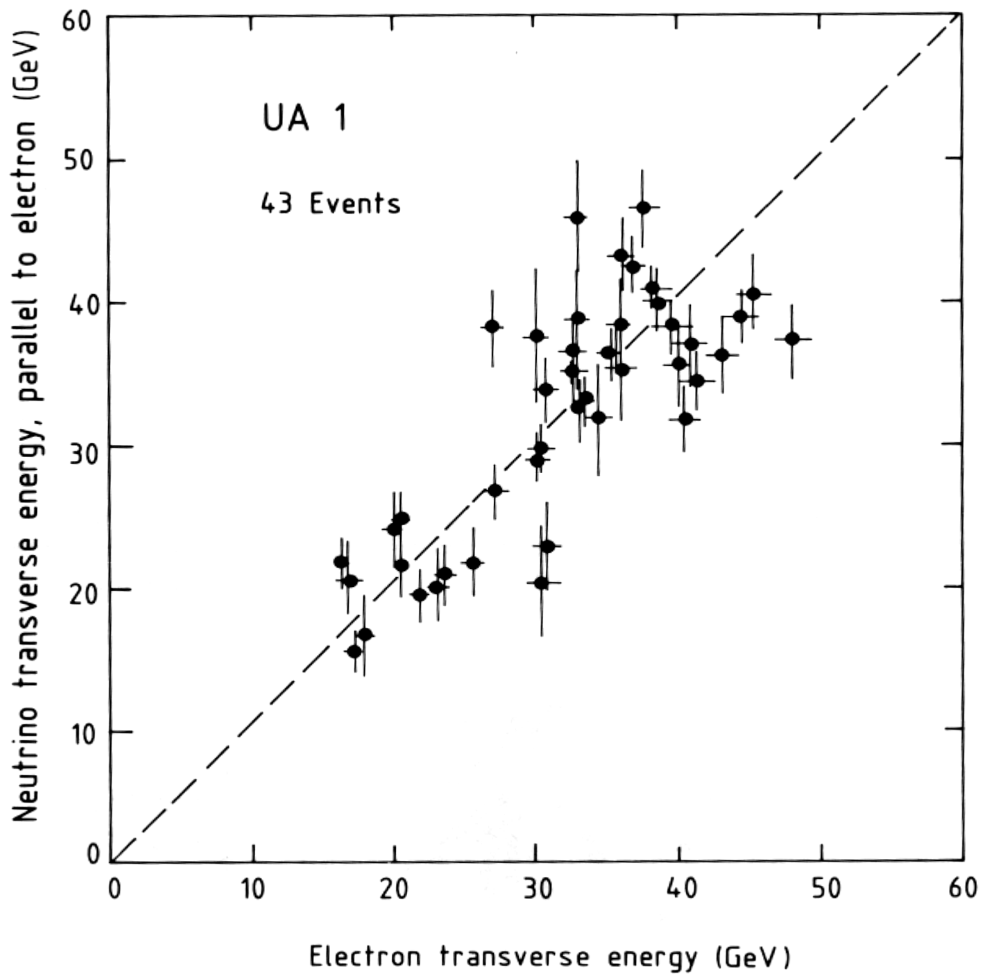




$W^- \rightarrow e\,\bar{\nu}$



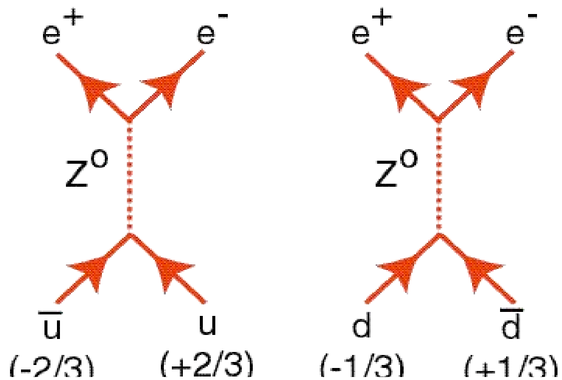


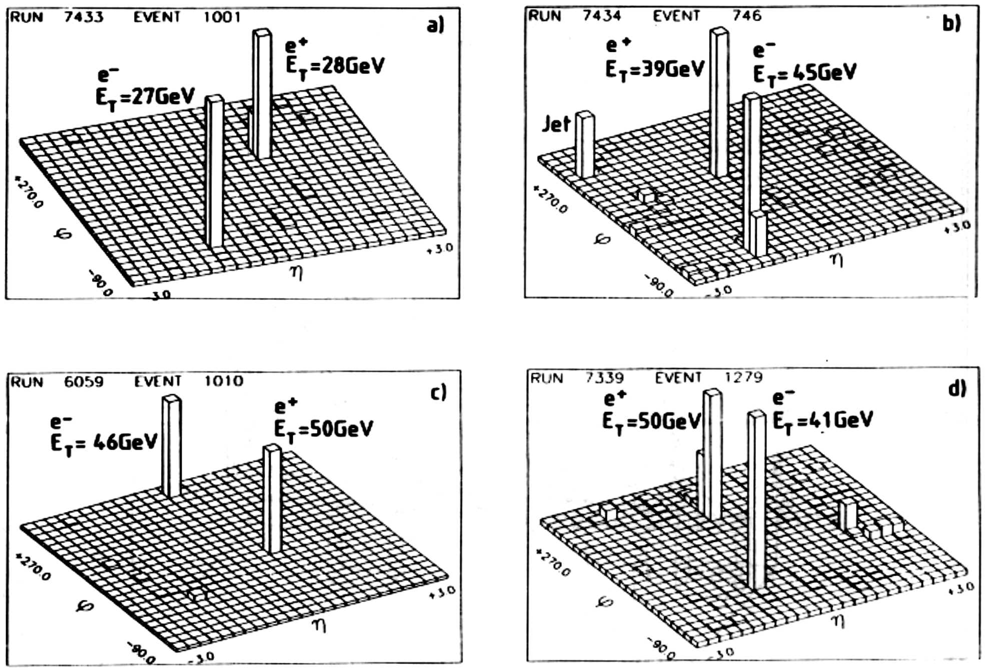


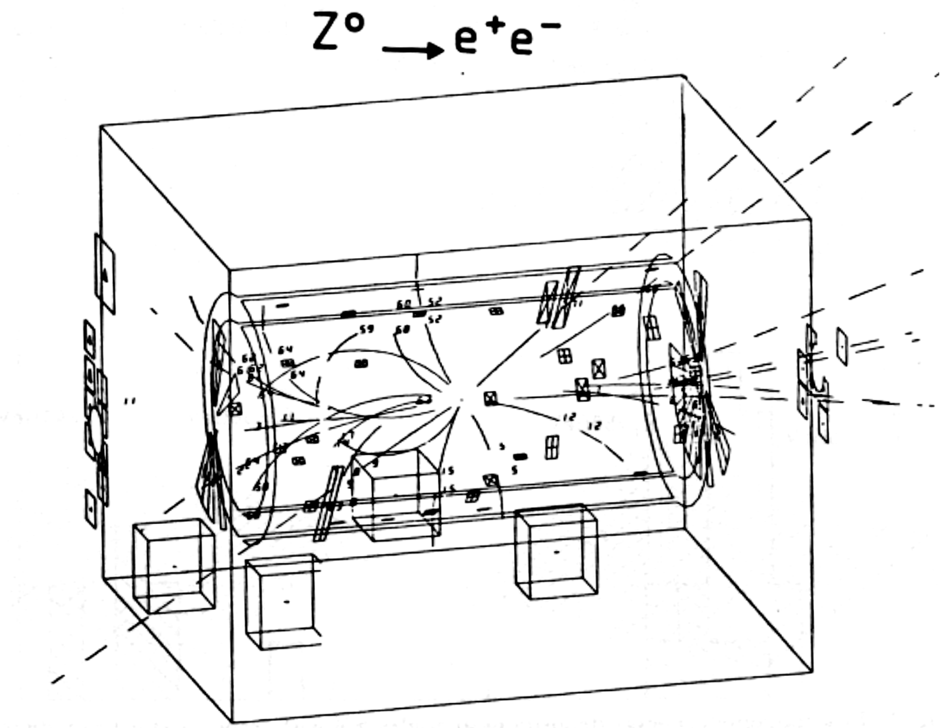
Angular distribution of the electron in the rest frame of the W

Correlation of electron and neutrino energies

The Z signal







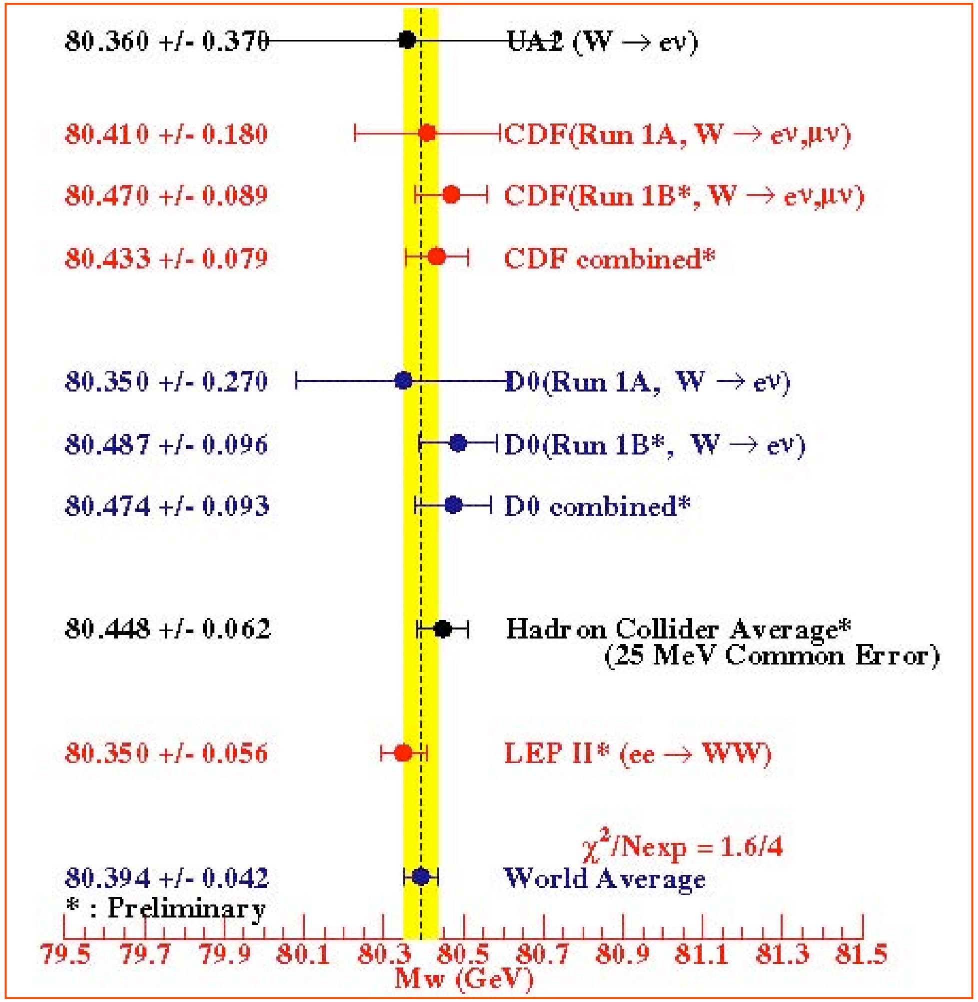
Lego plots of Z events

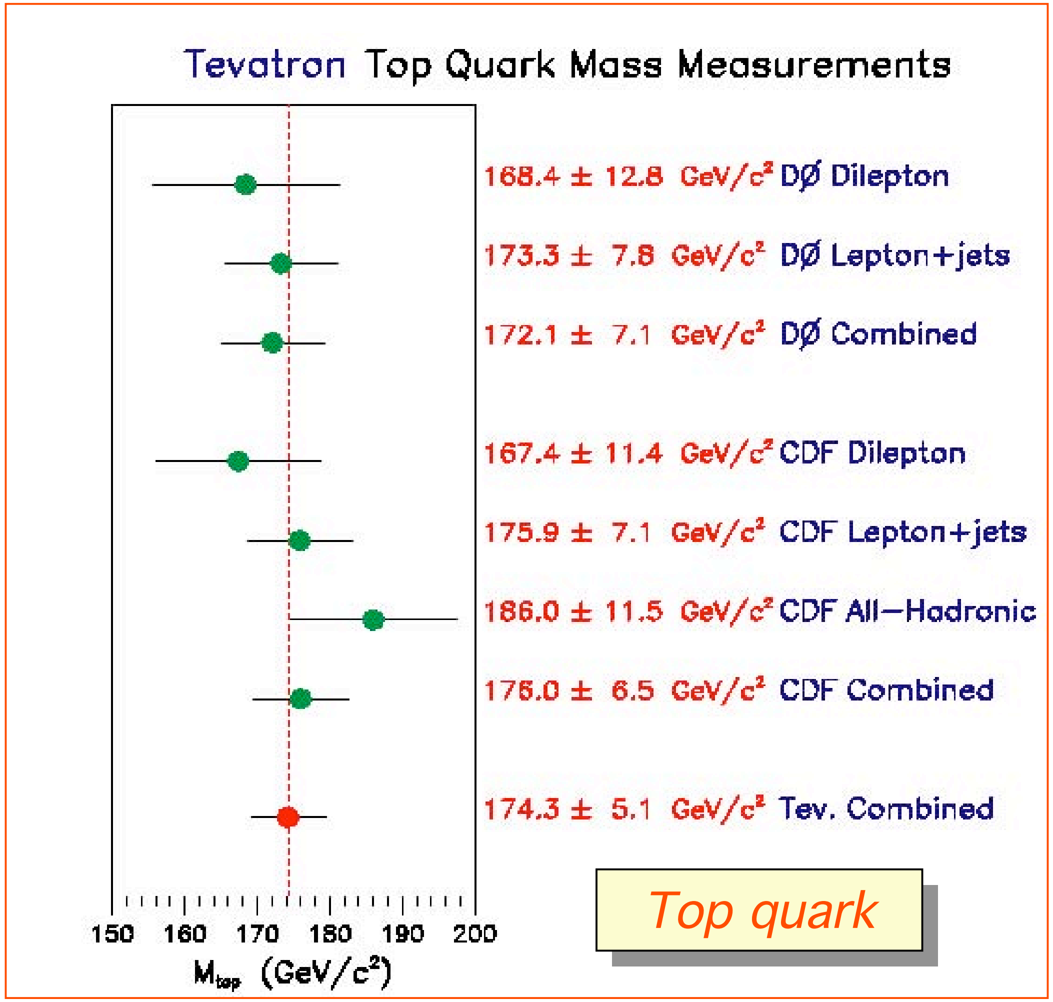
Somewhere in Sweden…..

Impact of p-pbar on HEP

- Since its initial introduction in HEP, the p-pbar technology has dominated the highest energy sector over the last 15 years
  - ⇨ The cooling technique has been generalised at CERN and Fermilab
  - ⇨ The UA1 detector approach has been followed in the LEP and Fermilab detectors
  - ⇨ LHC detectors also follow similar guidelines
- The initial UA1/UA2 results have been widely extended and generally confirmed
- The Top mass has been measured at the Tevatron.

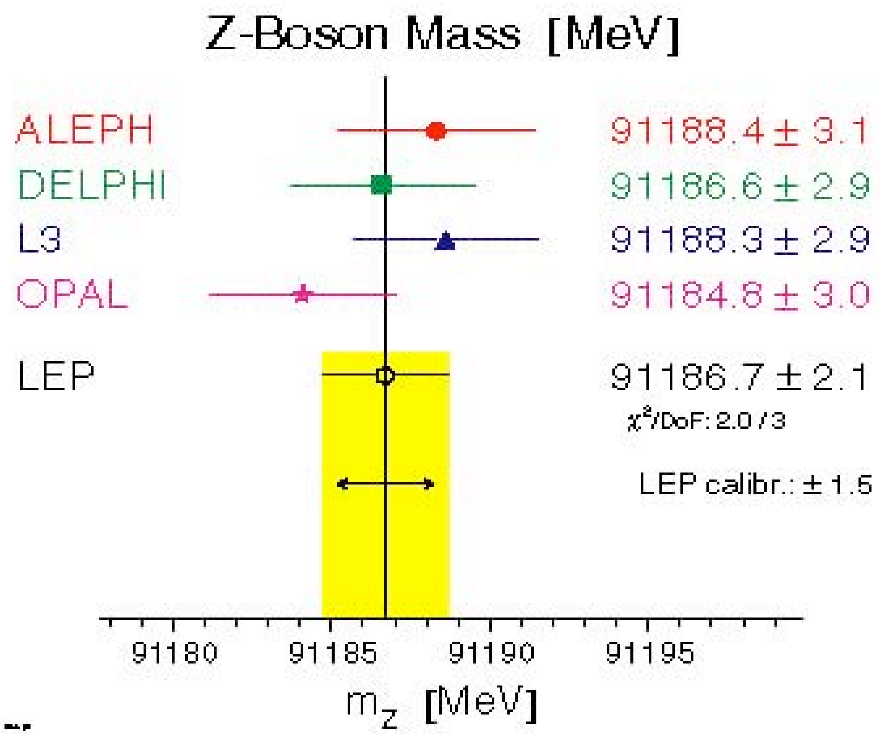
W mass

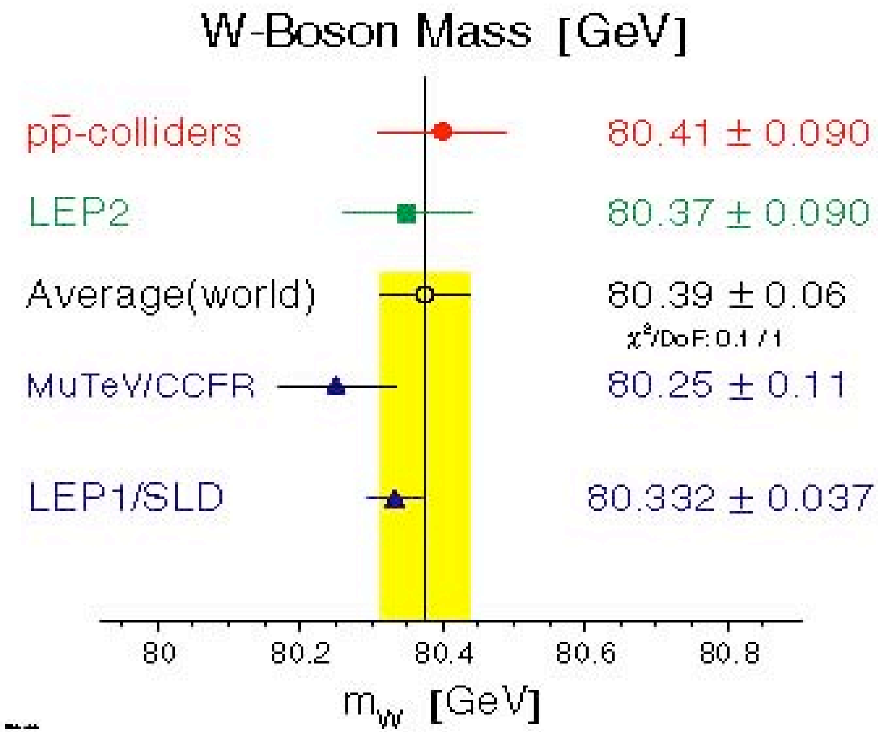




Top quark

Measurements of the IVB masses





Thank you !